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Seasonal performance rating of heat pump water heaters

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Abstract

Seasonal performance evaluation methods for water heaters are reviewed and an experimental method for rating air-source heat pump water heaters is presented. The rating method is based on measured heat pump performance during heat-up operation of particular products rather than a generic simulation model of heat pump performance. The measured performance is used in a correlation model of the heat pump unit in an annual load-cycle system performance simulation based on the TRNSYS simulation package.

Keywords: Heat pump; Water heating

1. Introduction

Heat pump water heaters based on air-source evaporators or solar-boosted evaporators are being adopted in many countries. In order to rate the performance of these systems against solar water heaters a seasonal performance assessment method is needed. This paper reviews seasonal performance evaluation methods for water heaters and presents a method for rating air-source heat pump water heaters. The annual performance of heat pump water heaters depends on climatic conditions and hot water load cycle delivery requirements. The seasonal performance of heat pump space heating systems is usually determined by instantaneous performance rating, and a climatic condition binning analysis method (Schibuola, 2000). The climatic binning performance method is based on the dependence of both the space heating (or cooling) load and the heat pump performance on ambient temperature. These methods cannot be used to evaluate the performance of heat pump water heaters as the hot water load has only a secondary dependence on climatic conditions.

Heat pump water heaters are renewable energy devices in the same manner as solar water heaters. Solar water heaters need to use auxiliary boosting during periods of low solar radiation while heat pump water heaters require an auxiliary input whenever the heating system operates. Both these classes of water heater draw the majority of their energy inputs from ambient or renewable energy of the atmosphere. In many countries some form of carbon credit or tax credit is given to purchasers of solar water heaters in partial recognition of the reduction in pollution that is achieved by these products. As the value of carbon credits increase authorities managing the credit schemes need to be able to accurately quantify the performance of particular products. Quantification of the annual performance of solar water heaters for specified load conditions is well established (ISO 9459-1, 1992; ISO 9459-2, 1994; ISO 9459-3, 1995; ISO/DIS 9459-4, 1992; ISO 9459-5, 1998), however, quantification of the annual performance of heat pump water heaters is not as well established. Most standards for air-source heat pump water heaters, such as the Canadian energy efficiency test (C745-00, 2000), rate the product for load cycle operation over a standard day and then scale the result for operation over a year. Although there are established load-cycle evaluation procedures for solar water heaters and solar-boosted heat pump water heaters there are no accepted methods

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for determining the annual load-cycle performance of air-source heat pump water heaters that account for the effect of climatic conditions on the heat pump performance. This paper outlines a rating scheme for air-source heat pump water heaters and application of the method to two different product configurations.

2. Heat pump water heaters

The most common form of heat-pump water heater is the air-to-water system based on a standard fan-coil evaporator and a water-cooled condenser. The condenser may be a separate heat exchanger with water pumped from the storage tank through the heat exchanger, or a wrap-around condenser coil on the tank with free convection on the hot water side of the tank wall. A range of solar boosted heat pump water heaters has also been developed with the solar collector acting as the evaporator (Charters et al., 1980; Morrison, 1994). The advantage of direct coupling of the heat pump circuit to the solar collector is that the solar input raises the evaporator temperature above ambient temperature and hence improves the heat pump performance. Air-source heat pumps are common in Europe and the USA while both solar boosted and air-source heat pumps are available in Australia. Water-to-water heat pumps have also been used in series with conventional solar water heaters. These systems are not considered in this project, as they have not gained market acceptance.

2.1. Air-source heat hump water heaters

In this project three heat pump water heaters were evaluated. One system was an integrated package with the heat pump compressor and evaporator mounted on top of the hot water tank and the condenser formed from a wrap-around coil on the tank as shown in Fig. 1. This system relies on natural convection of water in the tank over the condenser wall and hence avoids the parasitic energy losses associated with a water-circulating pump and external condenser. Two systems based on external heat exchangers were also evaluated. One system was an integrated package with an external condenser as shown in Fig. 2. The other system was a separate heat pump package with a water-circulating pump that could be connected to any existing hot water tank.

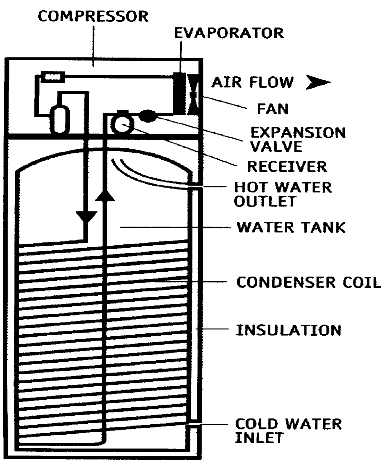

Fig. 1. Air-source heat pump water heater with wrap-around condenser coil.

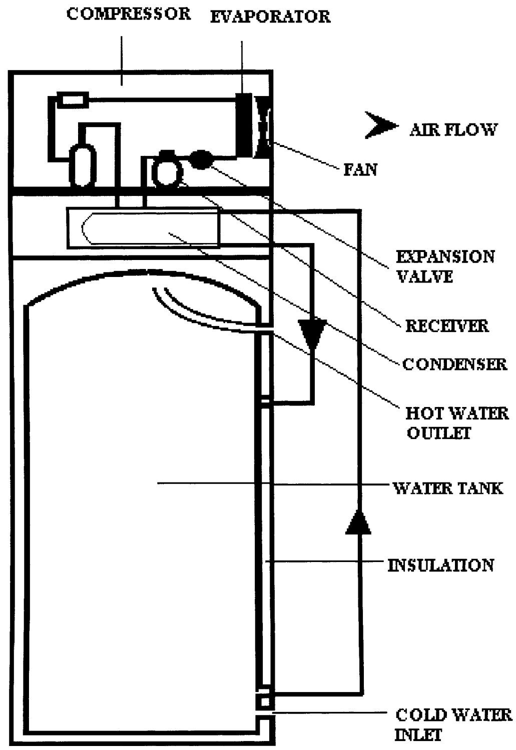

Fig. 2. Air-source heat pump water heater with external condenser.

3. Annual load cycle rating of water heaters

Due to the high cost of load cycle testing, calculation methods have been adopted in most countries to determine the annual energy use of water heaters. The approach adopted in Australia for load cycle rating of conventional gas and electric water heaters is to use the standing heat loss and draw-down test results and an average energy performance correlation to determine annual energy consumption under load cycle operating conditions (AS1056.4, 1997). A more detailed evaluation method for solar water heaters and solar-boosted heat pump water heaters is given in Australian standard

AS4234 (1994). Modelling the performance of a solar water heater or a heat pump water heater is more complicated than a conventional water heater because a short time step analysis must be carried out to account for variations of solar radiation, ambient temperature and relative humidity.

3.1. Annual performance rating of solar water heaters

The annual energy savings of solar water heaters under load cycle operating conditions can be determined using procedures based on a combination of component testing and mathematical simulation of load cycle operating conditions. Standards for such methods have been adopted in many countries and a draft standard is being developed by the International Standards Organisation (ISO/DIS 9459-4, 1992). As part of the simulation procedure, seasonal cold-water temperature and hot water use patterns are defined. The system performance is modelled using typical meteorological year (TMY) weather data and a short time step simulation of the output of the solar collector, the temperature conditions in the water tank and operation of the auxiliary energy input system. The load cycle simulation procedure accounts for temperature gradients in the water storage tank, variation of tank heat loss because of limited recovery rate of the auxiliary energy source, seasonal load patterns and ambient conditions. The long-term performance of solar water heaters can be readily evaluated from the efficiency of the solar collector, the heat loss characteristic of the tank and details of the solar collector plumbing and the collector loop flow. Evaluation of load cycle operation over a year for the location of interest requires inputs of component characteristics and hourly solar radiation and ambient temperature data for a typical climatic year. The procedure adopted in Australia for determining the performance of solar water heaters is based on the TRNSYS solar modelling package (Kline et al., 2000), with extensions to suit Australian solar equipment and Australian component testing procedures (Morrison, 1997).

3.2. Annual performance rating of solar boosted heat pump water heaters

The evaporator in a solar boosted heat pump water heater can be characterized experimentally as a standard unglazed solar collector using the test procedure specified in International Standard ISO 9806-3 (1995). The annual load cycle operation can then be modeled using a TRNSYS model similar to that used for solar water heaters. The procedure adopted in Australian Standard AS4234 is to base the performance of the solar-boosted evaporator on its efficiency as an unglazed solar collector with the addition of condensation heat gain on the flat absorber when the evaporator temperature is below the ambient dew point temperature. The TRNSYS model of the heat pump system incorporates measured characteristics of the heat pump compressor and a model of the condenser. The model solves for the instantaneous evaporator and condenser temperatures based on an energy balance between the evaporator, compressor and condenser using measured compressor and evaporator characteristics and models of the moisture condensation on the evaporator and the performance of the condenser in the storage tank. The water temperature in the storage tank is modelled using a modified version of the TYPE38 stratified tank model in TRNSYS (Morrison, 1997).

3.3. Annual performance rating of air-source heat pump water heaters

The performance of air-to-water heat pumps can be modelled by a similar procedure to that adopted for solar-boosted heat pump water heaters. However, characterisation of the performance of fan-coil evaporators is more difficult than for the flat plate evaporator in a solar-boosted heat pump. Although there is one less input to an air-source evaporator (there is no solar radiation) the quantification of the performance of fan-coil evaporators with performance enhancing features such as rippled or louvered fins and grooved tubes is significantly more complicated than for a flat plate evaporator. Condensation on a fan-coil evaporator is also more difficult to model than on flat plate evaporators as used in a solar boosted evaporator. As a result a direct measurement procedure was used in this investigation to characterise the heat pump system including evaporator, compressor and condenser rather than modelling individual components. This procedure can be used to determine product specific ratings without requiring knowledge of the construction of the heat pump system.

4. Performance monitoring

The objective of the test procedure used in this project was to treat the heat pump as a black-box and to limit measurements to inputs and outputs. Hence it is not necessary to know the internal states of the refrigerant system or details of the system design. The heat loss from the storage tank was measured separately and included in the annual load cycle analysis of the complete system. The measurement procedure used to quantify the performance of the heat pump system with a condenser separate from the hot water tank (Fig. 2) involved monitoring the water temperature rise and flow rate in the condenser and the power consumed by the compressor while the storage tank temperature is increased from cold to the maximum operating temperature. For the heat pump incorporating a wrap-around condenser (Fig. 1) the heat transfer to the tank was determined by measuring the change of temperature in the storage tank using a string of thermocouples inserted into the tank in place of the anode rod. For both types of systems the instantaneous capacity and power consumption of the heat pump was determined experimentally over a number of tank heat-up cycles for a range of ambient temperature and relative humidity conditions. The COP and power consumption were correlated using empirical models. The model was then used in an annual load cycle simulation program developed in the TRNSYS modelling package to determine the annual performance of the particular product under standardised weather conditions and load cycle requirements.

The COP and power consumption of the wrap-around heat pump (Fig. 1) is shown in Figs. 3 and 4 as a function of the temperature difference between the water in the tank (T_t) and ambient temperature (T_a) for a range of ambient relative humidity conditions. For a fixed relative humidity condition both the COP and power consumption correlate in a linear manner with the temperature difference $T_t - T_a$. A similar correlation was observed by Ito et al. (1999) for a different form of direct expansion heat pump water heater. The COP and power

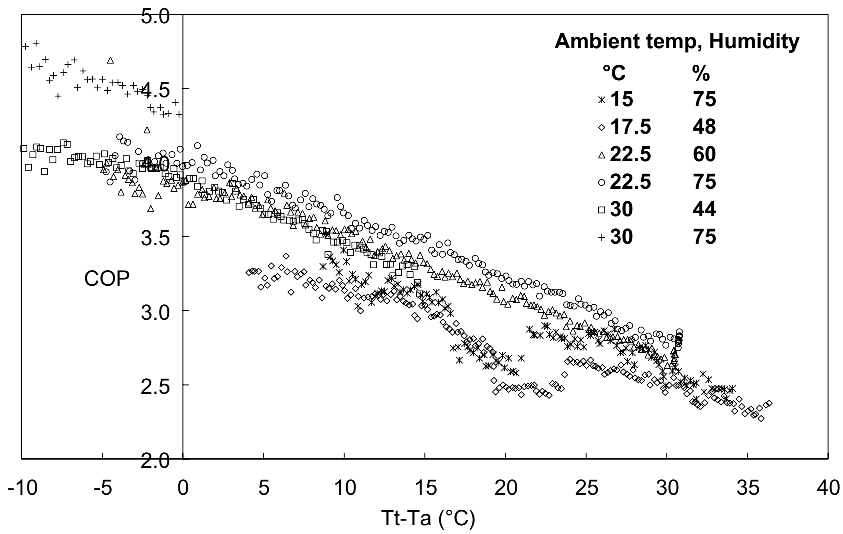

Fig. 3. Instantaneous COP versus condenser water temperature and ambient temperature.

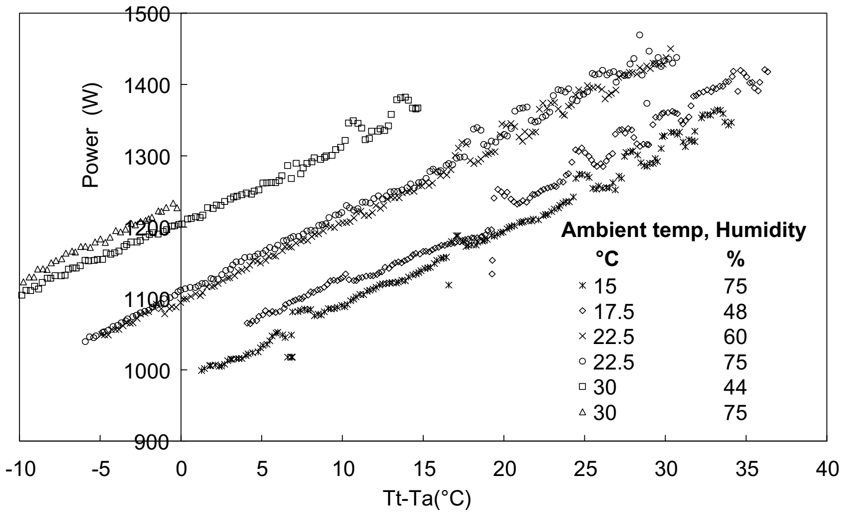

Fig. 4. Power consumption versus condenser water temperature and ambient temperature.

consumption both increase as the ambient relative humidity increase. Similar performance results were obtained for the system with an external pumped circulation condenser.

4.1. Correlation of heat pump performance

The test results shown in Figs. 3 and 4 indicate a linear relationship between both COP and power consumption and the primary temperature difference $T_t - T_a$. To correlate the measured data empirical models were developed based on the observed linear response to $T_t - T_a$ and a factor to account for the higher performance under high relative humidity conditions. The best correlation for COP was found to be a linear function in $T_t - T_a$ scaled by a multiplier between the wet bulb depression $(T_a - T_w)$ and the dew point depression $(T_a - T_d)$ as shown in Eq. (1):

$$\mathrm{COP} = [a_1 + a_2(T_t - T_a)]\left[1 - a_3\frac{T_a - T_w}{T_a - T_d}\right]. \quad (1)$$

The compressor power can be correlated with evaporator temperature and condenser temperature, however, as measurement of the internal refrigerant states

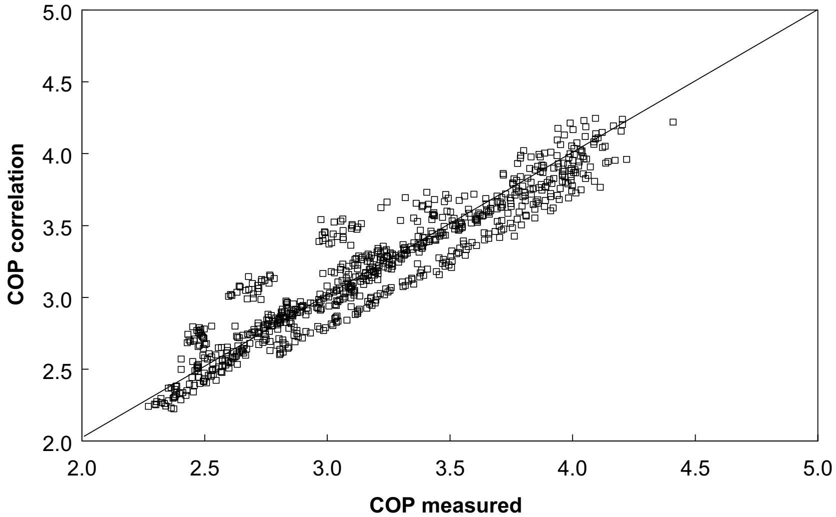

Fig. 5. Comparison of measured COP and corresponding value from the correlation model.

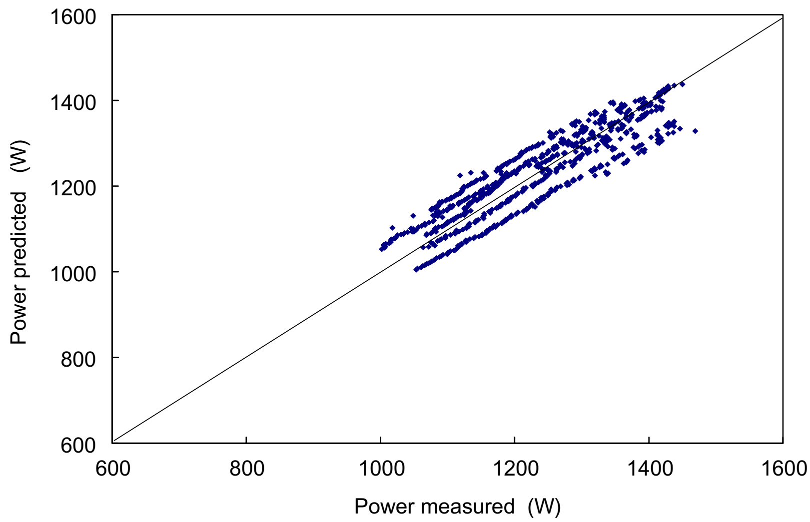

Fig. 6. Comparison of measured power consumption and corresponding value from the correlation model.

was not desired the power was correlated in terms of $T_t - T_a$ and $T_a - T_d$ as shown in Eq. (2):

$$\text{Power} = a_1 + a_2(T_t - T_a) + a_3(T_a - T_d) + a_4(T_a - T_d)^2. \tag{2}$$

Measured COP and compressor power are shown, in Figs. 3 and 4, for heat-up tests for six atmospheric relative humidity and temperature conditions. Comparison of the measured COP and power and the corresponding values indicated by the correlation functions (Eqs. (1) and (2)) are shown in Figs. 5 and 6. For the 760 test points shown in Fig. 5 the average difference between the measured COP and the COP indicated by the correlation model is 4%. The correlation of compressor power shown in Fig. 6 indicated an average error of 3% between measured and correlated power. Larger deviations were observed during transient operating periods near the beginning and end of each heat-up cycle.

The annual load cycle performance of the complete heat pump water heater was determined using the TRNSYS modelling package. The system performance was evaluated using a 0.5 h time step model to compute the temperature in the storage tank during load cycle operation. The performance of the heat pump module was evaluated using the COP and power correlation functions (Eqs. (1) and (2)) for the computed mean water temperature in the tank for the wrap-around condenser product and for the temperature in the bottom of the tank for the external pumped circulation condenser product.

For typical domestic hot water loads in Sydney Australia (40 MJ/day peak winter load) the annual COP of the integral condenser system was found to be 2.3% or 56% annual energy savings and for the external condenser system an annual COP of 1.8 or energy savings of 44%. The annual energy savings of these products is considerably lower than for flat plate solar water heaters or solar-boosted heat pump water heaters which for the climatic and load conditions considered have annual energy savings of 65–75%.

5. Conclusions

A procedure for annual load cycle rating of air-source heat pump water heaters has been demonstrated. The two air-source heat pump water heaters tested had significantly lower performance than typical solar water heaters or solar-boosted heat pump water heaters, however, the flexibility in the installation of these products means that they could be used in applications where solar water heaters cannot be considered.

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